

# Constraints on the Optical-IR extragalactic background from $\gamma$ -ray absorption studies

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**Abstract.** Very high energy (VHE,  $\gtrsim 0.1$  TeV) gamma-rays from extragalactic sources, interacting by  $\gamma - \gamma$  collisions with diffuse intergalactic radiation fields, provide an alternative way to constrain the diffuse background light, completely independent of direct measurements. The limits depend however on our knowledge of the physics of the gamma-ray sources. After clarifying the interplay between background light and VHE spectra, I summarize the extent and validity of the obtainable limits, and where future improvements can be expected.

**Keywords.** galaxies: active, BL Lacertae objects: general, cosmology: diffuse radiation, gamma rays: observations, infrared: galaxies.

## 1. Introduction

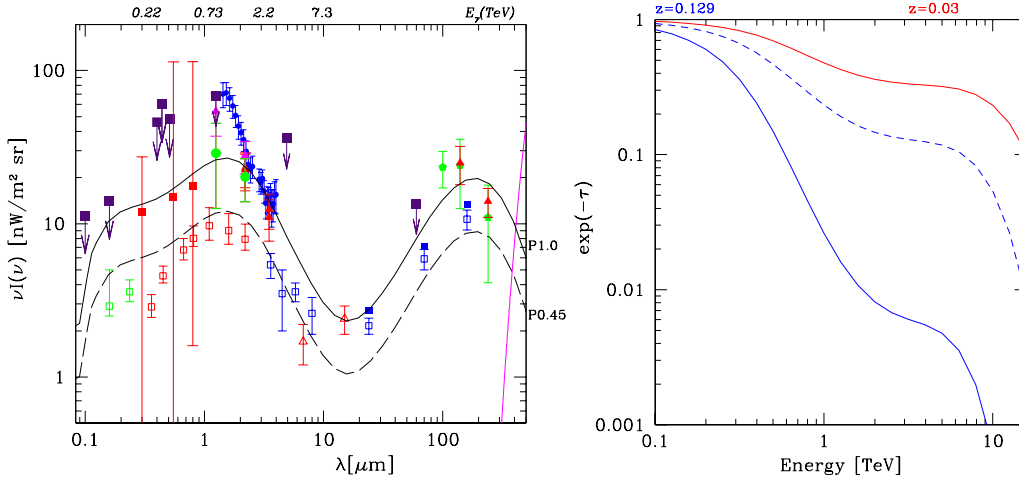
VHE  $\gamma$ -rays<sup>†</sup> from extragalactic sources provide an alternative and completely independent way, with respect to direct measurements, to probe the diffuse Extragalactic Background Light (EBL, from UV to far infrared wavelengths; see e.g. Hauser & Dwek 2001). This approach is based on the study of “absorption” features imprinted on the GeV-TeV spectra by the interaction of  $\gamma$ -rays with EBL photons through the pair-creation process ( $\gamma\gamma \rightarrow e^+e^-$ ; see e.g. Aharonian 2001 and refs therein). Blazars represent a very useful class of  $\gamma$ -ray beamers, being numerous over a wide range of redshifts, very luminous (enhanced by relativistic beaming) and long-lasting sources. However, they are far from being standard candles, and therefore the constraints on the EBL are *always* heavily dependent on our understanding of the blazar intrinsic emission and physical properties.

Nevertheless, it is possible to derive meaningful constraints if the intrinsic blazar properties implied by certain EBL spectra are very far from the known or expected range, and/or if they become inconsistent with other aspects of the blazars spectral energy distribution (SED). Observations in the last 5 years allowed a substantial progress, providing the stringest constraints to date. Here both the main results and the limits of their validity are discussed.

## 2. Diagnostics: how absorption deforms TeV spectra

The convolution of the  $\gamma$ - $\gamma$  cross section with the EBL spectrum yields an energy-dependent attenuation. Because the resulting optical depth  $\tau$  mostly increases with  $\gamma$ -ray energy, the observed  $\gamma$ -ray spectrum emerging at the end of the travel path is steeper than the initial, intrinsic spectrum emitted by the source (namely, the photon index

<sup>†</sup> In the following, ‘VHE’ and ‘TeV’ will be used as interchangeable terms, meaning about  $\pm 1$  decade around 1 TeV. The same for ‘HE’ (high-energy,  $> 0.1$  GeV) and ‘GeV’ terms. In fact, TeV and GeV are the energies at which atmospheric Cherenkov telescopes and the Fermi-LAT detector have the best sensitivity and resolution, respectively, for most astronomical spectra.



**Figure 1.** Left: SED of the EBL, as was discussed in year 2005 (from Aharonian et al. 2006). Open symbols show lower limits from galaxy counts, while filled symbols correspond to direct estimates. On the upper axis it is plotted the TeV energy corresponding to the peak of the  $\gamma - \gamma$  cross section. The two curves (identical except for normalization) are drawn as simple shapes reproducing the main EBL features. Right: the attenuation curves  $e^{-\tau}$  corresponding to the EBL curves in the left panel (lower solid and dotted lines), and at two different redshifts for the upper EBL curve (dark and grey solid lines). The attenuation curves represent directly the shape of an observed VHE spectrum, if the initial spectrum were a power-law parallel to the upper axis. All calculations performed assuming  $H_0 = 70$  km/s/Mpc,  $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ .

$\Gamma_{obs} \geq \Gamma_{int}$ ). This can be seen in Fig. 1, where the attenuation factor  $e^{-\tau}$  is plotted as a function of energy. Limits on the EBL can thus be derived if the intrinsic spectrum required by a particular EBL intensity (or shape) is too anomalous –typically too hard– with respect to the known physics of the source (e.g. Costamante et al. 2004). Several points can be noted from Fig. 1:

1) different EBL wavebands (having different slopes) affect each part of the  $\gamma$ -ray spectrum in a different way, yielding a complex deformation shape. However, over some ranges (namely 0.2-1 TeV and 2-8 TeV), it approximates a power-law shape. That is, if the intrinsic spectrum is a power-law, the observed spectrum can be well fitted by a power-law of steeper index.

2) The amount of steepening  $\Delta\Gamma$  increases both with distance and EBL intensity. Thus redshift gives leverage: the same uncertainty in EBL flux  $\Delta F_{EBL}$  causes a higher  $\Delta\Gamma$  at larger distances. More distant sources provides therefore more sensitivity for EBL constraints, but at the same time they suffer stronger attenuation, yielding much lower statistics. As a result, there is an optimal range of redshifts that provides the best compromise between EBL-sensitivity and statistical error, and thus gives the most stringent EBL limits. With the present detectors, it is around  $z \sim 0.15 - 0.25$ .

3) If the EBL number density  $n(\epsilon) \propto \epsilon^{-\beta}$  (i.e. the EBL SED  $\propto \lambda^{\beta-2}$ ), the optical depth  $\tau(E_\gamma)$  becomes  $\propto E_\gamma^{\beta-1}$ . Where  $\beta \approx 1$ , the optical depth becomes therefore independent of energy (Aharonian 2001). In such case *there is no steepening*: the absorbed spectrum reproduces the original shape, simply attenuated by a constant factor. This is what partly happens in the EBL waveband 3-10  $\mu\text{m}$ , according to all most recent EBL calculations (e.g. Franceschini et al. 2008, Dominguez et al. 2011, Gilmore et al. 2011, Kneiske & Dole 2010). It causes a flattening feature in the attenuation curve between

$\sim 1$ -2 and 8-9 TeV, where the observed  $\gamma$ -ray spectrum partly recovers its intrinsic slope and thus can appear harder than in the 0.2-1 TeV band <sup>†</sup>

4) Therefore, *NO cutoff is produced by EBL absorption between 0.2 and 8 TeV!* Any cutoff or steepening seen in this energy range should be intrinsic to the source spectrum. Fig. 1 also clarifies why almost all "data points" reported on the so-called "gamma-ray horizon" plots in literature (showing the  $E_\gamma$  at which  $\tau = 1$  as a function of redshift) are basically meaningless: there is no way to measure an EBL cutoff between 0.1 and 10 TeV using only VHE data. The only two EBL cutoffs are between the HE and VHE bands, i.e. between 20 and 200 GeV (thus requiring a Fermi-LAT spectrum), or above 8-10 TeV (for which only two blazars have been detected with sufficient statistics so far).

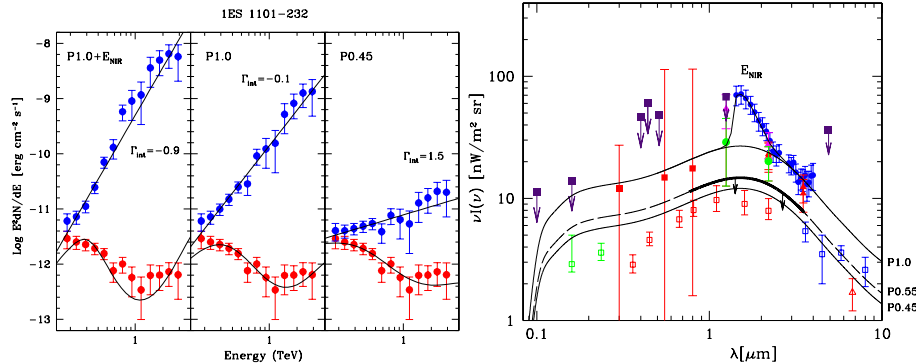
5) The  $\gamma$ -ray steepening is determined by the difference in optical depth between the two ends of an observed VHE band. Therefore any spectral steepening (and consequently any EBL upper limit) can always be counteracted and canceled by an appropriate increase of the optical depth (i.e. of the EBL flux) at the lower  $\gamma$ -ray energies, so to equalize the optical depths. In the 0.1-1 TeV range, this is obtained by increasing the UV flux with respect to the NIR flux (see Aharonian et al. 2006). Therefore, *any limit on the EBL always depends on the assumption on the UV flux*, by definition. All claims of "new" methods for "model-independent" or "shape-independent" EBL limits (e.g. Mazin & Raue 2007, Hinton & Hofmann 2009) are therefore essentially incorrect, even if their (often hidden) assumptions are reasonable and in fact commonly used (e.g. assuming that the UV flux is always lower than the Opt-NIR flux).

### 3. Optical-NIR constraints

Until 2005, the large uncertainty especially around 0.8-3  $\mu\text{m}$  (a factor 5-10 $\times$  between lower limits and direct estimates) caused a fundamental ambiguity in the interpretation of blazars gamma-ray spectra. An observed TeV spectrum could be the result either of a hard intrinsic spectrum attenuated by a high-density EBL, or of a soft intrinsic spectrum less absorbed by a low-density EBL. In both cases, the required intrinsic TeV spectrum was well within the typical range of spectra shown so far by blazars, so no useful constraint could be derived (with the exception of the 2-10  $\mu\text{m}$  range, see Aharonian et al. 2003). This ambiguity essentially undermined our capability to study blazars, since it corresponded to large differences both in energy and luminosity of their SED  $\gamma$ -ray peak.

In 2005, however, the HESS observations of the BL Lac objects 1ES 1101-232 ( $z=0.186$ ) and H 2356-309 ( $z=0.165$ ) provided a fundamental breakthrough (Aharonian et al. 2006). The observed  $\gamma$ -ray spectra (detected between 0.2 and 1-3 TeV) were much harder than expected for their redshift, implying extremely hard intrinsic spectra ( $\Gamma_{int} \lesssim 0$ ) in case of high EBL densities (Fig. 2). Such hard spectra were never seen in the closer, less absorbed objects and were at odds with all the known blazar physics and phenomenology. They were also not supported by same-epoch multiwavelength observations of their SED (Aharonian et al. 2007a). A low EBL intensity could instead accomodate all the new results within the typical range of blazar properties. Assuming that the intrinsic spectra were not harder than  $\Gamma=1.5$  an upper limit could be derived, which resulted very close to the lower limits given by the integrated light of galaxies (details in Aharonian et al. 2006). This result is now further corroborated by several other sources and observations (e.g. Aharonian et al. 2007b, Acciari et al. 2009, Albert et al. 2009).

<sup>†</sup> In fact,  $\gamma$ - $\gamma$  absorption can make a gamma-ray spectrum even *harder* than originally emitted, when  $\beta < 1$  (e.g. for a planckian distribution). This is indeed an effective way to explain very hard  $\gamma$ -ray spectra (Aharonian et al. 2008).



**Figure 2.** Left: The HESS spectra of 1ES 1101-232, corrected for absorption with three different EBL SEDs, as labelled (from Aharonian et al. 2006). Lower points (red): observed data. Upper points (blue): absorption-corrected data. The lines show the best fit power-laws to the reconstructed spectrum, and the corresponding shape after absorption. Right: upper limit for the EBL (black marked region), from the assumption of a blazar spectrum  $\Gamma \geq 1.5$ .

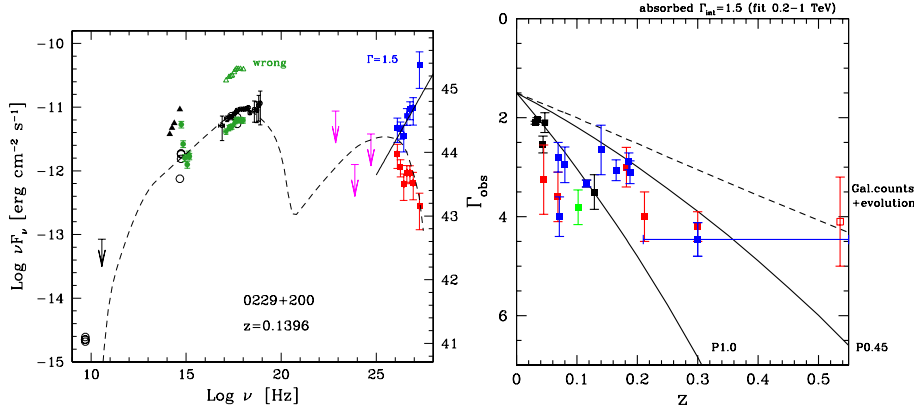
This result has three main consequences: 1) it pins down the origin of the EBL, showing that at these wavelengths it is strongly dominated by the direct starlight from galaxies, excluding a strong contribution from other sources like Pop-III stars (e.g. Santos et al. 2002); 2) it means that the intergalactic space is more transparent to  $\gamma$ -rays than previously thought, thus enlarging the  $\gamma$ -ray horizon; 3) it strongly reduces the ambiguity on blazars TeV spectra.

### 3.1. The (in)famous limit of $\Gamma=1.5$ .

There is a lot of confusion in literature on the validity of the  $\Gamma=1.5$  hardness limit and on the reasons of its adoption. It is important to understand that *this is NOT the hardest possible theoretical spectrum* in blazars, and was never introduced as such (see Aharonian et al. 2006). Indeed there are many possible mechanisms to produce extremely hard gamma-ray spectra in blazars, such as bulk-motion comptonization (Aharonian 2001), internal absorption on narrow-banded photon fields (Aharonian et al. 2008), uncooled particle acceleration spectra or fine-tuned shock acceleration (yielding however  $\Gamma \sim 1.2$ , e.g. Stecker et al. 2007), a low-energy cutoff in the particle distribution at very high energy (e.g. Katarzynski et al. 2006, Lefa et al. 2011), or relativistic Maxwellian distributions (e.g. Sauge & Henri 2004, Lefa et al. 2011).

The  $\Gamma=1.5$  limit is a reference value, a benchmark that so far marks *the borderline between reality and speculation*. Observations do show that blazars can have photon spectra with  $\Gamma \gtrsim 1.5$  (directly seen in synchrotron or inverse Compton emissions), and these can be produced with standard shock acceleration and cooling mechanisms without invoking special conditions or fine-tuning. On the other hand, much harder spectra have never been significantly detected in blazars so far, at high particle energies, neither directly or by synchrotron emission. The alternative scenarios, though not excluded by observations, are not suggested by them either, and in some cases require extreme fine-tuning to avoid conflicts with multiwavelength SED data.

Furthermore, the  $\Gamma=1.5$  value should not be considered a sharp, hard limit. At any given redshift, EBL absorption establishes a one-to-one relation between the observed and intrinsic  $\gamma$ -ray spectral slope. Thus a different assumption shifts the EBL limit accordingly, but only a large change (e.g.  $\Gamma_{int} < 1$ ) can effectively impact the conclusion of a low EBL. For example, in the case of 1ES 1101-232, a shift of  $\Delta\Gamma = 0.3$  (e.g. by assuming  $\Gamma_{int} \sim 1.2$ ) affects the EBL limit by no more than 10% (Aharonian et al. 2006).



**Figure 3.** Left: the SED of 1ES 0229+200, showing the correct X-ray data from Swift (filled green/grey points), at much lower flux than the wrong X-ray data (open triangles) used in Tavecchio et al. 2009. Right: observed VHE photon indices of all detected TeV blazars as a function of redshift. The lines represent the expected observed (i.e. absorbed) photon index of a source with an intrinsic spectrum  $\Gamma = 1.5$ , when fitted in the range 0.2–1 TeV, for different EBL levels (as labelled). The separation of the data from the lines at each redshift shows how much the intrinsic spectrum is harder or softer than 1.5. Adapted from Costamante 2006.

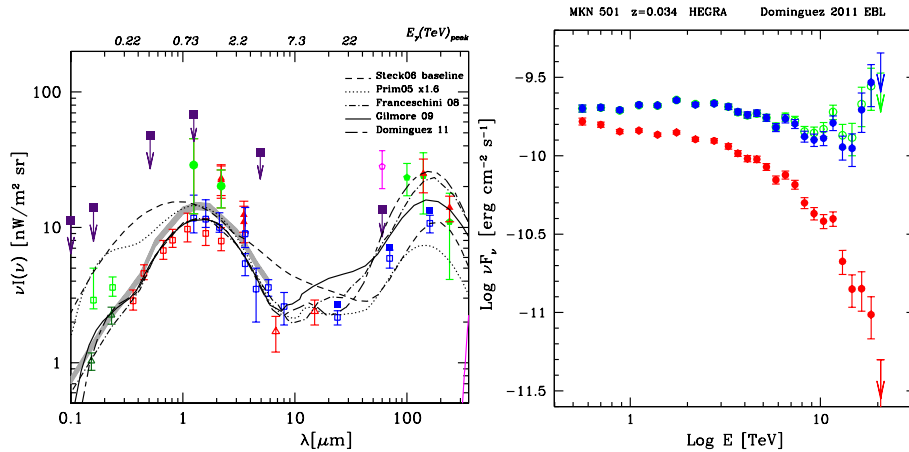
The Opt-NIR upper limit is therefore robust to such changes in blazar assumptions, which are of the same order of the statistical and systematic uncertainty in the  $\gamma$ -ray spectra.

The only relevant issue left, therefore, is to assess –theoretically and observationally– if blazars do have emission components characterized by *extremely* hard spectra (e.g.  $\Gamma = 0.7$  or less) or not, and when they produce them.

#### 4. Why a low EBL density is still the most likely solution.

Despite the several possible scenarios for producing very hard spectra in blazars, there are two main reasons why a low EBL density seems still the correct solution.

The first concerns the emitting particles spectrum. Most of these scenarios invoke very hard particle spectra, either as a pile-up/Maxwellian distribution or as a low-energy cut-off, and suppressing radiative cooling. These mechanisms look feasible even in a one-zone synchrotron self-Compton scenario for blazars (see Lefa et al. 2011 for a recent comprehensive discussion). However, since the synchrotron emission (which in these objects correspond to optical–X-ray energies) traces directly the particle spectrum, such hard features should appear in the synchrotron spectrum as well, at some energies and at least in some epochs. Instead, they have never been observed in more than 30 years of X-rays and optical/ir observations of blazars, requiring a “cosmic conspiracy” to always hide the hard emission below a more normal component or in seldom-observed bands (mm ?). Intriguingly, there was a recent claim of possible observational evidence for a low-energy cutoff in the Swift data of 1ES 0229+200, as an unusually high X-ray-to-UV flux ratio (Tavecchio et al. 2009). However, a bug was found in the calculation of the effective area of the X-ray data, and the correct result (see Fig. 3) show a spectrum in line with all other objects and observations. Future observations with ALMA (mm) and NuSTAR (hard X-ray) may provide further insights. Dropping the requirement of a hard particle spectrum, internal absorption on a narrow-banded photon field can make the gamma-ray spectrum extremely hard (Aharonian et al. 2008) However, large fluxes in the GeV range are required, and these seem now excluded by the low fluxes or non-detection of the hard-TeV sources with Fermi-LAT (Abdo et al. 2010).



**Figure 4.** Left: SED of the EBL with the most recent models. The grey band show the EBL upper limits in the Opt-NIR range (with the  $+1\sigma$  statistical uncertainty from the VHE data) re-calculated using the EBL shape by Franceschini et al. (2008). Right: HEGRA spectrum of Mkn 501, as observed (red, lower points) and absorption-corrected with two recent EBL-model calculations (Dominguez et al. 2011 and Gilmore et al. 2011, upper black-blue and grey-green points, respectively). Both cases show an upturn.

The second reason for a low EBL density (and thus for  $\Gamma_{int} \gtrsim 1.5$ ) is that a high EBL would require a dramatic change of blazar properties in a very narrow range of redshifts (see Fig. 3). A high EBL would create a sharp dichotomy in blazars spectra around  $z = 0.15$ : all sources below this redshift would have  $\Gamma \geq 1.5$ , while all blazars above this redshift would have always  $\Gamma < 1.5$ , all other properties being equal or very similar. There is no known reason, observational bias or evolution parameter that can explain such an abrupt change of properties in such small redshift range. Instead, a low EBL intensity makes the range of TeV blazar spectra consistent among each other at any redshift sampled so far.

Therefore, though not yet “bullet-proof”, until proven otherwise a low EBL seems the preferable solution according to Occam’s razor. (see also Madau & Silk 2005 for the cosmological problems to explain a high EBL flux).

## 5. The Chain of Constraints

Since the EBL photon field is the same for all sources, and evolving in redshift, the spectral-hardness limits from different blazars and in different energy bands can be combined to constrain the EBL over a wide range of wavelengths, and in a more stringent way than allowed by each single object (Costamante et al. 2004, Dwek & Krennrich 2005, Mazin & Raue 2007). Each new spectrum can take advantage of the previous limits, forming a chain of constraints that starts with (and depends on) the assumption on the UV flux. With the reasonable hypothesis that the UV background is lower than the Opt-NIR one (e.g. around 2-6 nW/m<sup>2</sup> sr), blazars spectra between 0.1 and 1 TeV pin down the Opt-NIR flux very close to the galaxy counts limit (Aharonian et al. 2006).

With this limit, the blazar spectra between  $\sim 1$  and 10 TeV (1ES 0229+200 Aharonian et al. 2007c and 1ES 1426+428, Aharonian et al. 2003) constrain the EBL spectrum between 2 and 10  $\mu\text{m}$  to a slope close to  $\lambda^{-1}$ , again very close to the lower limits from galaxy counts (Aharonian et al. 2007c). This is possible because the Opt-NIR limit precludes the possibility of increasing the flux at  $\sim 1 \mu\text{m}$  to reduce the difference in optical depth between 1 and 10 TeV (see Sect. 2).

The consequent upper limit at  $10\ \mu\text{m}$  constrains the rising of the EBL SED towards the far-infrared hump, which is determined by warm and cold dust emission. This band is probed by  $\gamma$ -rays between  $\sim 8$  and  $100\ \text{TeV}$ . So far, only two close-by objects have been measured up to  $15\text{--}20\ \text{TeV}$ , thanks to HEGRA observations: Mkn 421 ( $z=0.031$ , Aharonian et al. 1999) and Mkn 501 ( $z=0.034$ , Aharonian et al. 2001). Interestingly, the HEGRA spectrum of Mkn 501 seems to have problems with the most recent EBL calculations, which cause an up-turn or pile-up at the highest energies (see Fig. 4). This is the modern version of the so called “TeV-FIR background crisis” (see e.g. Aharonian 2001), caused years ago by a first very high estimate of the  $50\ \mu\text{m}$  EBL flux. However the information on warm dust and the  $\gamma$ -ray statistic are still insufficient to draw any sensible conclusion. More data  $> 10\ \text{TeV}$  are needed (hopefully from CTA).

## 6. Future and Conclusions

VHE data sample mainly the local EBL ( $z = 0 - 0.5$ ). To probe the EBL evolution over cosmic time and in the UV band, sources up to  $z = 3 - 4$  and data in the  $10\text{--}100\ \text{GeV}$  range are needed. The first results from Fermi-LAT (Abdo et al. 2010b) are in agreement with the VHE limits and with the most recent EBL evolution models. To this respect, however, GRBs might turn out to be more useful  $\gamma$ -ray sources, given that EBL and blazar-intrinsic evolutionary effects might be very difficult to disentangle (Reimer A. 2007).

At VHE, instead, CTA is NOT expected to improve the Opt-NIR limits per se, contrary to various claims. The reason is twofold. First, there is not much room for improvement ! The present upper limits already match the lower limits by galaxy counts quite closely (see Fig. 4) Second, even with infinite  $\gamma$ -ray statistics, it remains the unavoidable systematic uncertainty in blazar modeling. The small  $\Delta\Gamma \sim 0.1 - 0.3$  induced by the residual EBL uncertainty between lower and upper limits can be typically accomodated with very small changes in blazar parameters, for a given set of multiwavelength data.

The main question to be addressed is if our blazar assumptions are correct (and in such case the EBL is already pinned down) or are not (and in this case by how much). In the latter case, the entire construction must be revisited, since it is our understanding of the gamma-ray sources that changes completely. It is on this aspect, on blazar physics, that CTA is expected to provide the most significant improvements and to test our assumptions by finding counter-examples. This can be done by monitoring more low-redshift objects in the TeV range (to detect directly  $\Gamma < 1$ ) and by measuring more high-redshift spectra (to find those for which  $\Gamma = 1.5$  is incompatible with galaxy counts; Costamante 2007).

In conclusion, a low EBL close to galaxy counts seems the “convergent solution”, despite some uncertainties on blazar physics. However, there are still some fundamental aspects of blazars’ acceleration and emission mechanisms not yet understood, which present and future observations are testing. The EBL limits obtained so far are robust against small changes in blazars assumptions, but they all depend, by construction, on the assumption of a low diffuse UV flux.

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## DISCUSSION

**Q (K. Mattila):** Does MAGIC give additional (or better) constraints to the EBL at optical wavelengths, where it should be more sensitive than HESS because of its lower  $\gamma$ -ray energy range ? (I am referring to the 2008 Science paper on 3C279).

**A:** In this case (3C 279), not really. The problem is the much higher uncertainty in the spectrum. This is also caused by 1) the smaller detected band (less than half a decade, with respect to a full decade in energy for 1ES 1101-232 and the other BL Lacs), and 2) the much lower S/N. The lower  $\gamma$ -ray energy range does probe slightly shorter wavelengths, but it also reduces the sensitivity of the  $\gamma$ -ray spectrum to EBL changes, with respect to the 0.2-2 TeV range, despite the higher redshift. Note that in the blue-UV range ("max EBL" curve in their Fig. S2), the given values are basically arbitrary, and should not be considered limits at all (a higher UV flux makes also the Magic spectrum softer, see Sect 2). In summary, that observation does not provide more stringent constraints on the optical background, though the detection itself corroborates the idea of a low overall EBL (adopting historical GeV peak fluxes for 3C 279). It is also important to remind that, for this source, there is the further systematic uncertainty of internal absorption on UV photons from the broad line region (this object has broad lines in the optical spectrum).